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1 Stiffness of dowel-type timber connections under 2 pre-yield oscillating loads

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6 **Abstract**

The dynamic behaviour of timber structures in service is becoming a more important consideration in design as modern engineered wood products allow longer spans and taller timber buildings, which can be sensitive to dynamic loading such as that from wind or footfall. Connections in timber structures have a pronounced effect on their structural behaviour. In dowel-type connections, the fasteners bend under load and embed into the surrounding timber and, since embedment is a nonlinear process, the stiffness of those connections varies depending on the nature of the applied load. Here, single-dowel connections are tested under cyclic loads representative of in-service vibration. One-sided and reversed cyclic loads are applied. The specimen stiffness is observed to reduce with the amplitude of one-sided cyclic load. For small-amplitude one-sided load, the specimen stiffness is seen to tend towards that predicted by an elastic model, and an analytical elastic model is presented to represent the embedment resistance of the timber and the behaviour of the connector.

7 *Keywords:* timber, connection, dowel, dynamic, vibration, serviceability

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8 1. Introduction

9 Dowel-type connections make a significant contribution to the stiffness of
10 timber structures in which they are used, and most timber structures employ
11 dowel-type connections in the form of either nails, screws, bolts or plain
12 dowels. In recent years, engineered wood products such as glued-laminated
13 and cross-laminated timber have allowed timber to be used in more ambitious
14 structures, such as long-span bridge structures and multi-storey buildings,
15 by allowing large member and panel sizes not possible in sawn timber. Such
16 structures require thorough design for serviceability conditions, including
17 vibration under dynamic loads such as wind and footfall.

18 The behaviour of dowel-type connections includes nonlinear and irre-
19 versible components, even under loads well below their nominal yield load.
20 For example, the stiffness exhibited when a load is first applied is different
21 to that when the load is removed and reapplied. Therefore, if the connec-
22 tion stiffness is to be represented by an equivalent linear elastic stiffness, as
23 is the case in most structural engineering analysis, then that stiffness must
24 be chosen to be appropriate to the nature of the applied load. This study
25 investigates the stiffness of dowel-type connections under the cyclic loads re-
26 sulting from in-service structural vibration, and presents an analytical model
27 based on the elastic material properties of the timber and connector, which
28 is shown to predict the underlying elastic response on which the nonlinear
29 behaviour is superimposed.

30 The nonlinear stiffness under in-service loads differs from that under seis-
31 mic loads, which have been widely studied and in which gross plastic be-
32 haviour occurs in timber and connectors. This research therefore extends

the field by providing empirical evidence of the stiffness and energy dissipation in dowel-type connections under in-service dynamic loads, and the basis of a predictive model for their stiffness in those conditions.

2. Background

There has been a great deal of research into the dynamic performance of timber structures with dowel-type connections under the forces and displacements associated with seismic loading, measuring stiffness, and its variation of with the amplitude and duration of the applied cyclic load [1, 2, 3, 4, 5, 6]. There has been far less research into the stiffness of connections under the pre-yield loads associated with in-service loading by dynamic forces such as wind and footfall.

Chui and Ni [7] carried out cyclic tests on connections with gradually increasing amplitude of load, and observed the development of hysteresis loops. A lower-stiffness region at low load was observed to occur as a result of local plastic behaviour around the dowel. This behaviour had been widely noted, but not thoroughly investigated until the study by Dorn et al. [8], who attributed it to the contact stiffness between the imperfect surface of the timber, and the relatively smooth and hard surface of the steel. Dorn et al. studied serviceability loads, but focussed primarily on monotonic, rather than cyclic loading.

This study adds to the current knowledge of the vibration behaviour of timber structures by measuring the stiffness in complete connections under one-sided and reversed loads representative of in-service vibration. An analytical model is then applied to assess the underlying elastic stiffness of the

connections onto which the nonlinear behaviour, considered to be due to the interaction between dowel and timber at the contact surface, is superimposed.

The connection is modelled as a beam, representing the steel dowel, on a foundation representing the embedment resistance of the timber. The beam-on-foundation model was first applied to timber connections by Kuenzi [9], and beam on foundation models were later used to model nailed connections, using non-linear embedment parameters for timber and connector [10, 11, 12].

The stress-strain behaviour of steel can be readily used to evaluate the behaviour of the beam in its elastic and plastic ranges. The foundation modulus, in contrast, has conventionally been empirically defined [7, 13, 14]. Embedment has also been modelled using the finite element method [15, 16]. A model for embedment must take into account the contact behaviour and friction at the interface between dowel and timber. Finite-element models therefore must include contact elements, which adds to their computational intensity.

This study sought to define and test an analytical model for embedment and connection stiffness. Such a model must represent the behaviour of an orthotropic elastic material, the timber, around a hole loaded by frictional contact with a rigid circular section, the dowel. This situation is generally referred to as a pin-loaded plate, and is common to timber and fibre-reinforced composite structures. A general analytical solution was defined by Lekhnitskii [17], and was developed by other researchers for analysis of the stress distribution around the hole [18, 19, 20, 21]. Reynolds et al. [22] extended the application of the method to prediction of displacements, and applied the solution by Zhang and Ueng [21] to estimate the stiffness measured in cyclic

82 embedment tests on half-hole embedment specimens according to ASTM
83 D5764 [23].

84 In this study, the analytical stress function defined by Hyer and Klang
85 [20] is used and extended to predict the stiffness of complete simplified con-
86 nections. The model is compared with experimental results for cyclic loads
87 representative of in-service vibration.

88 3. Materials and Methods

89 The experimental work in this study used Norway spruce (*Picea abies*)
90 glued-laminated timber (glulam), delivered with a cross-section of 190mm by
91 200mm, made up of five 40mm laminates. The glulam was strength-graded
92 as GL28h according to EN 1194 [24]. After delivery, its moisture content was
93 measured by electrical resistance to be 11.3%. The specimens were cut from
94 the glulam and stored in a controlled environment at 18-22°C and 60-65%
95 relative humidity for a period of 7 months, which was assumed to be sufficient
96 for equilibrium moisture content to be achieved. After testing, 7 specimens
97 were cut from the single-dowel connection test specimens for evaluation of
98 this equilibrium moisture content according to EN 13183 [25]. The moisture
99 content had a mean of 11.9% with a coefficient of variation of 0.05. The
100 density of the glulam was measured as 458kg/m³, which could be corrected
101 to give 461kg/m³ at 12% moisture content. This is 12% higher than the
102 410kg/m³ for standard GL28h.

103 The nominally 12mm dowels were specified by the supplier as C16 bright
104 steel according to EN 10277 Part 2 [26]. The dowels were measured as having
105 a diameter of 11.8mm, and the holes in the timber were predrilled using a

12mm auger drill bit. The steel plates were 6mm thick, and inserted into a 7mm slot in the timber piece.

Specimens were rejected if they contained a substantial visible defect in the surface of the timber within 25mm of the holes for the connectors. Otherwise, the specimens were used as delivered, incorporating defects elsewhere in the timber.

3.1. *Single-dowel connection test*

The single-dowel connection test was intended to investigate the processes which contribute to stiffness in a connection in which the dowel transmits force from the timber to a steel plate in a central slot. Loads in tension and compression were applied to each specimen to investigate the effect of the different stress distributions in the timber on stiffness. The specimen was made symmetrical, with a connection at each end, which removed the need to anchor the specimen, since a stiff anchorage could not be readily achieved in tension. Only the movement of the loading head was measured, so the measured deformation represented the sum of the deformations in the two connections. The movement of the loading head was measured using a $\pm 1\text{mm}$ LVDT on an adjustable steel mounting. The moving rod of the LVDT was attached to the loading head adjacent to the jaws in which the steel plates were clamped, and the fixed part of the LVDT was attached to a steel mounting attached to the test bed. In the tests with fully reversed loading, the displacements were out of the range of the LVDT, and so the internal displacement sensor in the loading machine was used. The LVDT which was used had no connection between the moving rod and the fixed body, the rod moved freely through the coil, and was attached by a magnet to the loading

131 head. This ensured that no force was transferred to the mounting of the
132 LVDT, so that there would be no movement of the LVDT body during the
133 test. This was crucial given the small differential movements, of the order of
134 microns, which were to be measured. It was assumed that the steel plates
135 did not slip in the jaws of the loading machine, and that their deformation
136 was negligible in comparison with the deformation in the connections.

137 BS EN 383 [27] gives recommended dimensions for a symmetrical static
138 embedment test specimen parallel-to-grain, and so these dimensions were
139 used to aid comparisons with work by other researchers. No guidance is given
140 in EN 383 [27] for tests in tension perpendicular-to-grain, so the specimen
141 dimensions were determined to match the compression tests in that standard,
142 with the distance between the dowels specified to be double that between the
143 dowel and the test bed in the standard. The thickness of the specimens was
144 chosen as 190mm, so that the failure loads for one and three plastic hinges
145 were close for both parallel and perpendicular to grain, according to Eurocode
146 5 [28]. Although the loads applied were well below those necessary for any
147 plastic hinges to form, this was considered to represent a common situation,
148 since it is recommended that connections are designed to form one or three
149 plastic hinges to ensure ductility. The specimens are shown schematically in
150 Figure 1.

151 The embedment strength of the timber was calculated based on the
152 density of 461kg/m^3 , according to Eurocode 5 [28]. This gave an embed-
153 ment strength of 33N/mm^2 parallel to grain and 22N/mm^2 perpendicular.
154 These embedment strengths were used to calculate the expected connection
155 strengths of 14.2kN parallel, and 11.7kN perpendicular.

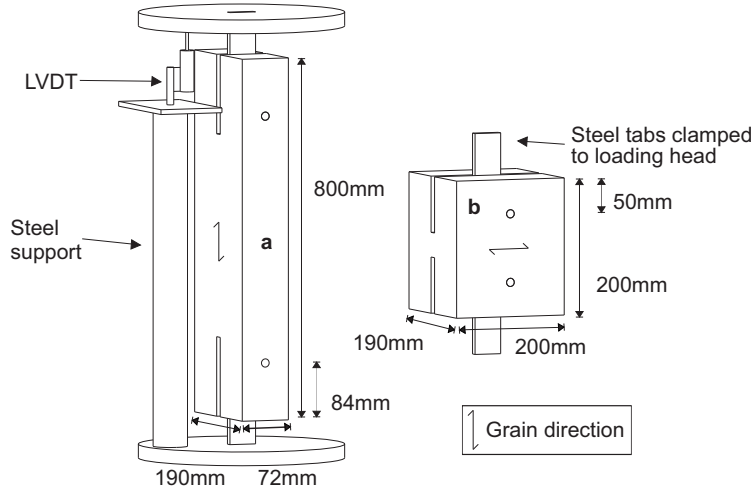


Figure 1: Test setup and specimen dimensions for single-dowel connection tests **a** parallel to grain and **b** perpendicular to grain

3.2. Loading

The magnitude and form of oscillating load was chosen to be a simplified representation of the different forms of load which could result from in-service vibration. Since problematic vibration is commonly a result of resonance, such loads can be expected to have a dominant sinusoidal component [29, 30]. A sinusoidal variation of displacement was therefore applied, the mean and amplitude of which was defined by the R -ratio, given by $R = F_{max}/F_{min}$ where F_{max} is the maximum load in the compressive sense and F_{min} the minimum. R -ratios of 1.2, 10 and -1 were used.

$R=1.2$ and $R=10$ represent different ratios between the extremes of force in a one-sided oscillating load. One-sided loading occurs, for example, in vertical footfall-induced vibration, in which the mean load applied by the self-weight of the structure is larger than the dynamic load applied by footfall, so that the load on the structure is never reversed. One-sided loading also occurs

170 in along-wind vibration of structures, in which the mean wind force is larger
171 than the dynamic component caused by turbulence. $R=-1$ represents fully-
172 reversed loading, which occurs in across-wind vibration or lateral footfall-
173 induced vibration in which the mean load is zero.

174 The frequency of the oscillating load was 1Hz, chosen to be within the
175 range of vertical and lateral structural vibration. Vertical footfall-induced
176 vibration generally occurs at frequencies higher than 1Hz, and the lateral
177 mode natural frequency of tall buildings can be lower, but 1Hz was considered
178 to be a reasonable frequency to investigate the general principles of behaviour
179 under oscillating load in this range. The magnitude of the oscillating load
180 was characterized by the peak value, and the tests used peak loads of 20% and
181 40% of the characteristic yield load of the connection according to Eurocode
182 5 [28]. These levels of load are considered to be approximately representative
183 of the range of load imposed on a structural component during everyday use
184 of a structure.

185 The duration of cyclic loading was chosen to ensure that any transient
186 effects could be observed and that a single value of either stiffness or energy
187 dissipation could be measured which was representative of the long-term
188 steady-state behaviour. The load was applied for 1000 cycles, which proved
189 sufficient for the stiffness and energy dissipation to reach a representative
190 steady state. The tests were carried out in displacement control, since it
191 was found that the nonlinearity in the response caused the servo-hydraulic
192 loading machine to become unstable in load control. The displacements for
193 the peak and trough of the cyclic loads were determined at the start of the
194 test.

195 The sequence of single-dowel connection tests is shown in Table 1. Each
 196 specimen was tested for each load level, R -ratio and load direction. Three
 197 specimens were tested for each grain orientation, six specimens in total. The
 198 tests with lower peak loads were carried out first, so that each test represented
 199 the highest load the specimen had seen, and tests with $R=1.2$ were carried
 200 out before those with $R=10$, with the $R=-1$ test last of all. Since the purpose
 201 of this study was to measure steady-state behaviour after repeated cycles of
 202 load, it was considered that the previous loading at the same or lower load
 203 level would not have a significant effect on the measured stiffness and energy
 204 dissipation, though it is expected that the previous loading may cause the
 205 specimen to reach the steady-state more quickly.

206 3.3. *Friction test*

207 In addition to the elastic material properties for the timber, the elastic
 208 stress-function model presented in Section 5 required the friction coefficient
 209 between the dowel and the surrounding timber. This was estimated using the
 210 test setup shown schematically in Figure 2. The friction coefficient between
 211 dowel and timber was estimated based on the ratio between the force applied
 212 to the dowel to produce continuous movement and the normal force applied
 213 to the specimens, which was either 20% or 40% of their predicted embedment
 214 strength given in Section 3.1. Six specimens were tested, three parallel to
 215 grain and three perpendicular, and their dimensions are shown in Figure 2.
 216 The specimens were taken from the same batch of Norway spruce glulam
 217 used for the single-dowel connection tests. As in the case of the single-dowel
 218 connection specimens, the holes were drilled using a pillar drill and an auger
 219 bit, and the bright mild steel dowel was cleaned and de-greased before testing.

Table 1: Single-dowel connection tests

Grain orientation	Load sequence	Load direction	Peak load		R -Ratio
			% of yield	kN	
Parallel	1)	Compression	20%	2.84	1.2
	2)		20%	2.84	10
	3)		40%	5.68	1.2
	4)		40%	5.68	10
	5)	Tension	20%	2.84	1.2
	6)		20%	2.84	10
	7)		40%	5.68	1.2
	8)		40%	5.68	10
	9)	Reversed	40%	5.68	-1
Perpendicular	1)	Compression	20%	2.34	1.2
	2)		20%	2.34	10
	3)		40%	4.68	1.2
	4)		40%	4.68	10
	5)	Tension	20%	2.34	1.2
	6)		20%	2.34	10
	7)		40%	4.68	1.2
	8)		40%	4.68	10
	9)	Reversed	40%	4.68	-1

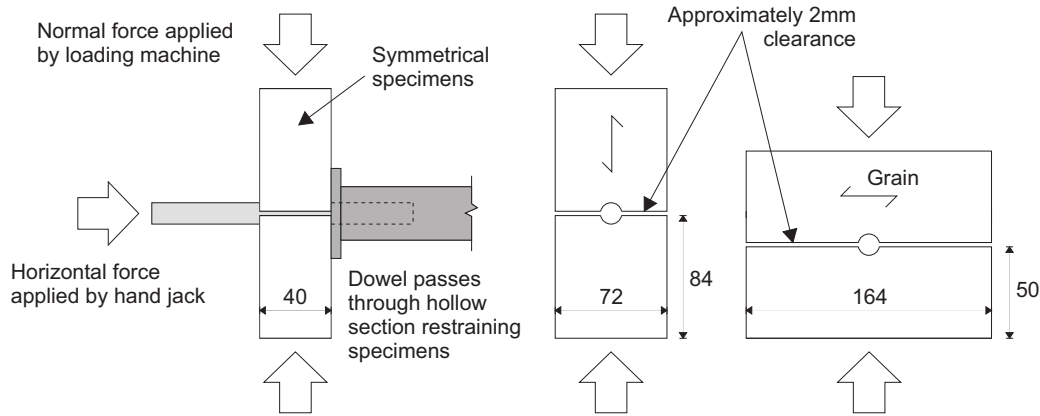


Figure 2: Schematic diagram of friction test setup

It was noted that the orientation of the friction force in this test was different to the orientation of the friction around the dowel as it embeds into the surrounding timber. Nonetheless, this test was considered to provide a reasonable estimate of the coefficient of friction, given that a more extensive study of friction between steel and timber by McKenzie and Karpovich [31] showed little variation of friction coefficient with angle to grain.

4. Experimental Results and Discussion

Under its first loading, the gradual compression of the contact surface between dowel and timber, as well as viscoelastic behaviour in the timber itself, lead to a transient variation in stiffness. These effects were observed by calculating the secant stiffness for every cycle of applied load during the test.

Figure 3 shows the force-displacement plots for a single cycle at each of the three R -ratios on the same parallel-to-grain specimen. The 100th and 900th cycles are shown in each case. Figure 3 also indicates how the secant

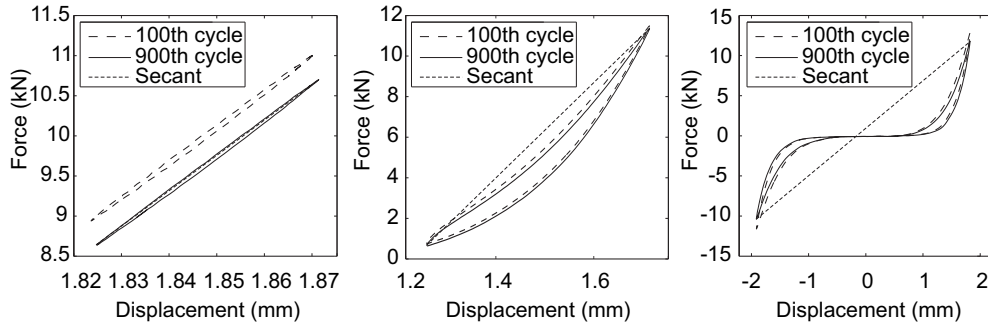


Figure 3: Force-displacement plots for parallel-to-grain tests in compression with $R=1.2$, left, $R=10$, centre, and $R=-1$, right - the gradient of the dotted line is the secant stiffness for the 900th cycle in each case

stiffness was calculated in each case.

The slack section in the $R=-1$ plot, where the loading head moves with very little force applied, is due both to the clearance between the dowel and the holes in the steel plates that load the specimen and the gap formed by irreversible behaviour in the surface of the timber. The dowels, nominally 12mm, were measured as having a diameter of 11.8mm, and the holes in the steel plate were drilled to 12.5mm. The total slack due to this clearance in each of the two dowels was therefore approximately 1.4mm, and so accounts for a significant proportion of the displacement at near-zero force shown in the $R=-1$ plot in Figure 3.

The results shown in Figure 3 are for parallel-to-grain tests in compression. The other grain and load orientations show qualitatively the same behaviour: at $R=1.2$ the force-displacement behaviour is close to linear with a small area inside the hysteretic loop in comparison with $R=10$, at which more non-linearity is apparent, and at $R=-1$ gap formation is seen to influence the force-displacement response.

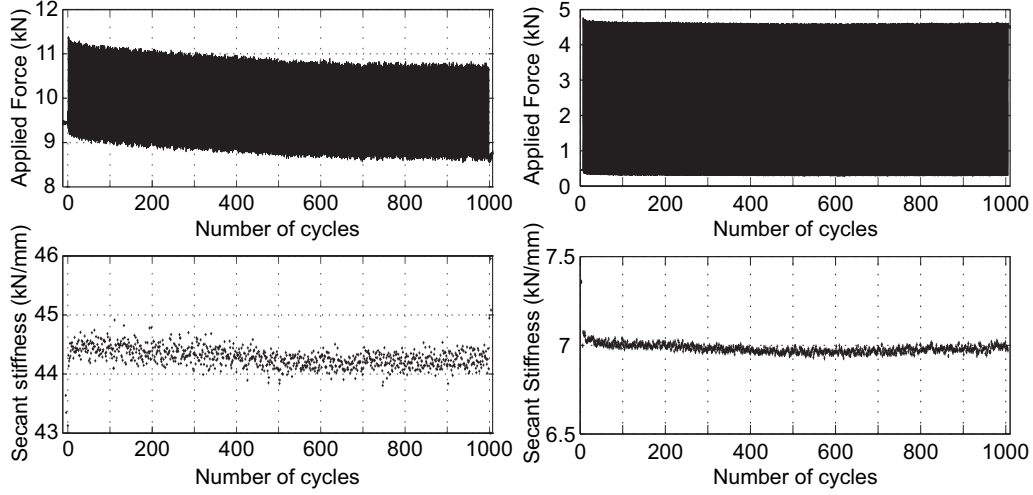


Figure 4: Stiffness in each cycle of load through the test, for a specimen loaded in compression parallel to grain to 40% of its characteristic yield load, with an R -ratio of 1.2 (left hand plots) and in tension perpendicular to grain to 20% of its characteristic yield load, with an R -ratio of 10 (right hand plots).

251 The graphs in Figure 4 show the variation of secant stiffness through
 252 a 1000-cycle test. In both the tests shown, the stiffness tends towards an
 253 approximately constant value during the test, after variation in the first 500
 254 to 700 cycles. In some tests, there was still evidence of variation in stiffness
 255 after 1000 cycles. In those cases, the measured stiffness may differ slightly
 256 from the steady-state value. It is acknowledged that there may be longer-
 257 term effects which are not apparent in the duration of these tests. The
 258 scatter of stiffness is considered to be primarily due to measurement noise,
 259 and there is far less scatter in the tests at $R=10$ due to the larger differential
 260 displacements and forces being measured.

261 It can be seen from Figure 4 that, since the test is carried out in dis-
 262 placement control, the force applied to the specimen reduces with time due

263 to viscoelastic behaviour in the timber. This results in the shift in the force-
264 displacement diagram between the 100th and 900th cycles in Figure 3. This
265 shift only affects the secant stiffness in the case of the fully-reversed load
266 with $R=-1$, since it represents a gap formation in the connection, and the
267 gap is not crossed in one-sided loading.

268 In the other grain and load orientations same qualitative behaviour was
269 observed: a tendency of stiffness towards a relatively consistent value over
270 the course of the test. The quantitative differences between the specimens
271 are presented in Figure 5.

272 Figure 5 shows the secant stiffness measured in the single-dowel tests
273 with $R=10$, $R=-1$ and $R=1.2$. The secant stiffness is expressed as the mean
274 value over the final 300 cycles in the test. This was taken to be a reasonable
275 estimate of the steady-state values.

276 More scatter can be seen in the measured stiffness in the perpendicular-
277 to-grain tests than in the parallel-to-grain tests. In the parallel-to-grain
278 tests, the stiffness, plotted in Figure 5, is observed to increase slightly with
279 the peak value of the applied load. It is considered that the increase in
280 stiffness is due to the higher applied force compressing the surface of the
281 timber and improving the stiffness of the contact between dowel and timber.
282 This suggests that as the contact between the dowel and timber improves,
283 the stiffness of the connection tends towards a value which represents a rigid
284 contact surface. This concept is important in considering how the connection
285 is modelled in Section 5, since it suggests that, to predict the steady-state
286 stiffness and energy dissipation in the connector, a model with a rigid contact
287 surface may be appropriate.

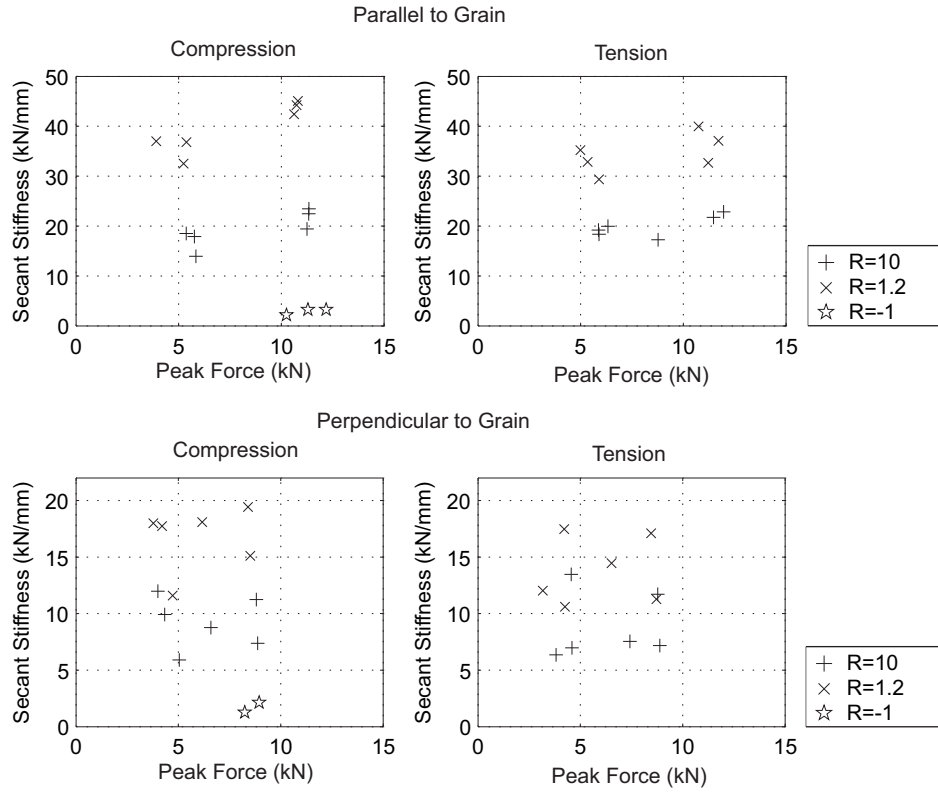


Figure 5: Secant stiffness for single-dowel connection tests

288 The perpendicular-to-grain tests in Figure 5 do not show the same ten-
 289 dency for an increase in stiffness with the peak value of the applied load.
 290 In the perpendicular-to-grain direction, therefore, it appears that the plastic
 291 processes in the contact surface are largely complete at 20% of the charac-
 292 teristic yield load, and have little further effect at higher loads.

293 Student's t -test [33] was applied to estimate the likelihood that the ob-
 294 served variation in stiffness with the magnitude of the peak load was a result
 295 of experimental scatter. The test was developed for analysis of small samples
 296 such as the three repetitions in these tests, and returns a probability that a

Table 2: Student’s t -test applied to investigate the effect of variation in peak load on the secant stiffness measured in single-dowel connection tests: \bar{d} mean of the difference in stiffness at each peak load, s_x is the standard deviation of those differences, n is the number of specimens, ν is the number of degrees of freedom for the t -distribution, t is the test statistic and p the probability that the null hypothesis is true

	\bar{d}	s_x	n	ν	t	p
Tension						
Perpendicular	0.91	1.42	3	2	1.11	0.38
Parallel	4.11	0.73	3	2	9.70	0.01
Compression						
Perpendicular	1.60	1.46	3	2	1.90	0.20
Parallel	8.46	1.33	3	2	10.99	0.01

297 null hypothesis, that both samples are taken from populations with the same
 298 mean, is true. Since tests with different peak loads were carried out on each
 299 specimen, a paired-variable t -test was used. The application to the parallel
 300 to grain tests shown in Table 2 therefore returns the probability p that the
 301 change in peak load from 20% to 40% of the characteristic yield load has no
 302 influence on the secant stiffness.

303 The results show that, in the parallel-to-grain tests, it is extremely likely
 304 that there is an influence of peak load on stiffness, with probabilities of 0.01
 305 in each case that the null hypothesis is true. The influence of peak load in
 306 the perpendicular-to-grain tests is less clear, as shown in the table.

307 The Eurocode 5 slip modulus represents current design guidance to cal-

308 culate the stiffness of a connection [28]. Applying that guidance to this
309 specimen results in a predicted stiffness of 10.2kN/mm, without including
310 the slip due to the oversize of the hole in the steel plate. That guidance
311 makes no allowance for grain direction, and can be seen to be a significant
312 underestimate for the parallel-to-grain tests, especially with $R=1.2$, where
313 the underestimate is by as much as a factor of 4. The Eurocode slip modulus
314 is intended for calculation of deflections under static loads, rather than such
315 small-amplitude oscillating load, and this is considered to be the reason for
316 this discrepancy. The result therefore highlights the importance of the nature
317 of the applied load to the stiffness of this type of connection.

318 Figure 5 shows that the measured secant stiffnesses under $R=1.2$ loads
319 are generally higher than those with $R=10$. Since each specimen was tested
320 at each amplitude, it was possible to analyse these results as paired variables.
321 The ratio of the stiffness at $R=10$ to that at $R=1.2$ was compared for every
322 load level and every specimen, and the results are shown in Figure 6. It can be
323 seen that in every case, the stiffness measured at $R=10$ is lower than that at
324 $R=1.2$, and that the ratio is in a relatively concentrated range, with a mean
325 value of 0.56 for all the tests. An independent-variable t -test comparing the
326 parallel- and perpendicular-to-grain ratios shows that it is likely there is an
327 influence of grain direction, with a probability of 0.06 that that two samples
328 come from populations with the same mean. The mean ratio of the $R=-1$
329 secant stiffness to that at $R=1.2$ is 0.07 in the parallel-to-grain orientation
330 and 0.12 perpendicular to grain.

331 The reduced stiffness at $R=-1$ includes the slip due to the oversize of the
332 holes in the steel plates. If the deflection, estimated as 1.4mm, due to this

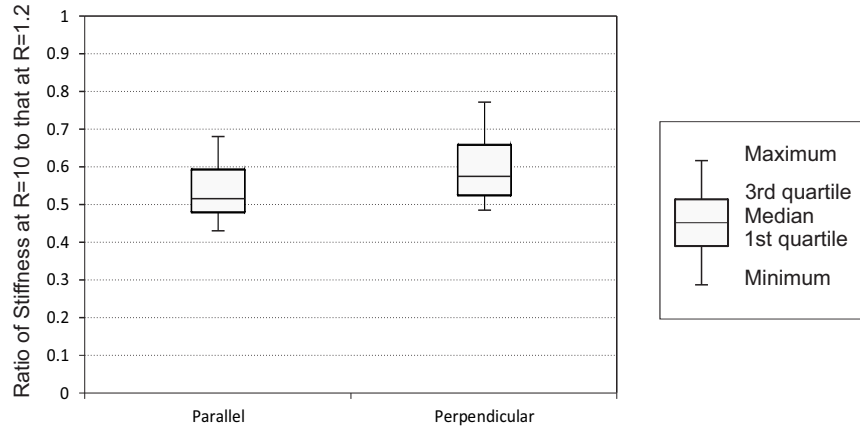


Figure 6: Box plot for reduction in stiffness between $R=1.2$ and $R=10$ for the collated results of tests in tension and compression, at 20% and 40% of the characteristic yield load

333 oversized is excluded, then the mean ratio of the $R=-1$ secant stiffness to that
 334 at $R=1.2$ is 0.12 parallel to grain and 0.17 perpendicular. The reduction
 335 in stiffness between $R=1.2$ and the reversed load with $R=-1$ is due to a
 336 combination of the low stiffness for low load in embedment, gap formation
 337 in the timber and the oversized of the hole in the steel plate. Some of this
 338 gap formation will have occurred in viscoelastic behaviour during the one-
 339 sided tests at $R=1.2$ and $R=10$, which were carried out before the reversed
 340 $R=-1$ tests. In this sense, the secant stiffness for the $R=-1$ tests presented
 341 here is related to the particular loading history applied to the specimens, in
 342 a way that is not the case for the one-sided tests, in which the viscoelastic
 343 behaviour is considered to significantly affect the overall displacement, but
 344 not the secant stiffness.

345 5. Model

346 5.1. Foundation modulus

347 Reynolds et al. [22] showed that the stiffness of the embedment test could
348 be modelled analytically by superposition of stress functions for a pin-loaded
349 half-hole in a semi-infinite orthotropic plate. This study uses a different
350 version of the stress function to Reynolds et al. [22], one proposed by Hyer
351 and Klang [20], which represents the stress field around a complete hole in a
352 pin-loaded orthotropic plate, in order to model the behaviour of a complete
353 connection.

354 Hyer and Klang used the stress function to calculate the stresses around
355 the hole edge. It has been shown that such a stress function can be used
356 to calculate the field of displacements in the timber around the dowel, and
357 so the movement of the dowel relative to a particular fixed point [22]. The
358 stress function is two dimensional for the plane-stress condition and thus,
359 when used to calculate the embedment stiffness of the timber around the
360 dowel, gives the stiffness of a unit thickness of material along the dowel. It
361 also, therefore, does not allow for some effects of the full elastic foundation
362 provided by the timber, such as the effect of non-uniform loading along the
363 dowel's length.

364 The solution by Hyer and Klang [20] was slightly modified by adding the
365 term in p , the mean stress in the member, as proposed by Echavarría et al.
366 [19] to account for the finite extent of the loaded member. The resulting
367 equation for the stress functions $\phi_{1,2}$ is given in (1) and (2). The trans-
368 formed coordinates $\zeta_{1,2}$, the roots of the characteristic equation $\mu_{1,2}$ and the
369 coefficients a_n and b_n representing the load on the hole edge are all as defined

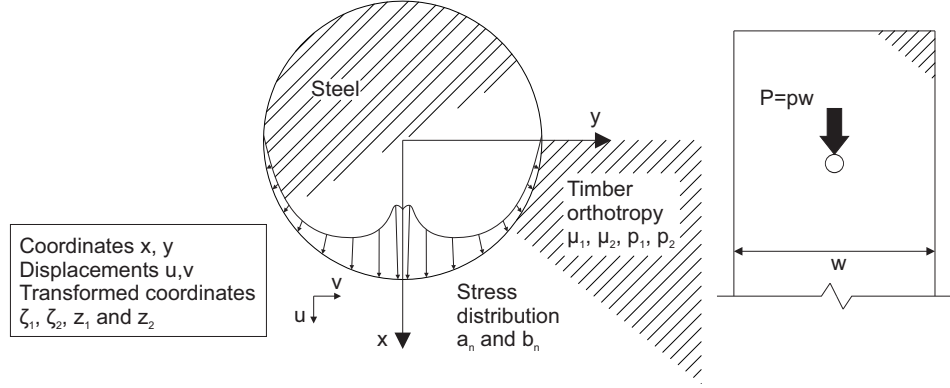


Figure 7: Illustration showing notation for the stress function model for embedment

by Hyer and Klang [20] and Lekhnitskii [17], and the solution follows Hyer
 and Klang's method. The effect of friction is to alter the distribution of load
 around the hole edge, and is therefore reflected in the coefficients a_n and b_n ,
 which are calculated by an iterative process [20]. The notation is illustrated
 in Figure 7.

$$\phi_1 = a_0 \ln \zeta_1 + \frac{p}{2} \left(\left(\frac{-i}{\mu_1 - \mu_2} \right) \frac{1}{\zeta_1} + \frac{z_1}{\mu_1^2 - \mu_2^2} \right) + \sum_{n=1}^{\infty} \frac{a_n}{\zeta_1^n} \quad (1)$$

$$\phi_2 = b_0 \ln \zeta_2 + \frac{p}{2} \left(\left(\frac{-i}{\mu_2 - \mu_1} \right) \frac{1}{\zeta_2} + \frac{z_2}{\mu_2^2 - \mu_1^2} \right) + \sum_{n=1}^{\infty} \frac{b_n}{\zeta_2^n} \quad (2)$$

The displacements in the loaded direction u can then be calculated ac-
 cording to 3 [17], where p_1 and p_2 are calculated from the material properties,
 as given by Lekhnitskii [17].

$$u = 2\text{Re}(p_1 \Phi_1 + p_2 \Phi_2) \quad (3)$$

Figure 8 shows the result of superimposing two stress functions with loads
 in opposite directions to give the field of deformation in the specimen. The

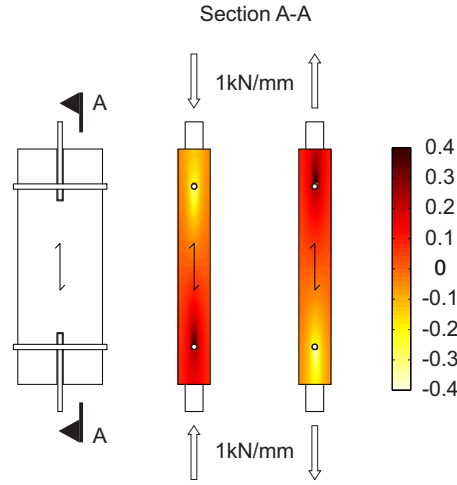


Figure 8: Field of vertical displacement in mm in the timber under a dowel load of 1kN per mm thickness, used to calculate the foundation modulus for the connection

displacement of each dowel relative to the line of zero displacement mid way between the dowels is then used to calculate a foundation modulus for the single-dowel connection tests. As shown by Hyer and Klang [20], if the dowel fits tightly into the hole, the relationship between force and dowel displacement is linear, so the foundation modulus is constant with dowel displacement.

It should be noted that, in contrast to current methods for assessment of the foundation modulus, this model takes into account the distance between connectors. This includes both by the elastic deformation of the timber between the dowels under the mean stress, which would normally be accounted for elsewhere in the analysis, and the effect of the stress concentration which gradually equalizes along the length of the member.

392 5.2. *Beam on foundation*

393 The stress function allows for the embedment behaviour of the dowel in
394 the timber. In the single-dowel connection tests, there is deformation of
395 the dowel, and this is represented by a beam-on-foundation model, in which
396 the resistance of the timber to embedment is represented by a foundation
397 modulus, and the dowel by a beam to which the appropriate loads are ap-
398 plied. Since the steady-state cyclic embedment behaviour under the smaller-
399 amplitude $R=1.2$ loads appears to be close to linear-elastic, the foundation
400 provided by the timber was considered as elastic for that form of load. The
401 model is not intended to represent the reduced stiffnesses at $R=10$ and $R=-1$
402 which have been treated empirically in this study.

403 For the connections with a central flitch plate used in this study, the de-
404 flection which defines the connection stiffness is at the centre of the beam,
405 where the load is applied. The beam is of finite length, equal to the length of
406 the dowel, and the reaction at the foundation is proportional to its displace-
407 ment: a Winkler foundation [34]. A widely-used analytical solution exists
408 for this geometry of a beam on elastic foundation, and is used in this study
409 [35].

410 5.3. *Comparison with experiment*

411 The model was used with the material properties shown in Table 3. Since
412 the timber was graded and the moisture content was within 1.5% of the
413 standard 12% value for all of the specimens, it was considered appropriate to
414 use the material properties given for glulam in EN 1194 [24]. That standard
415 does not provide the Poisson's ratio, so that value was taken as given by
416 Bodig and Jayne [36] for Spruce. The friction test described in Section 3.3

Table 3: Material properties used in connection stiffness calculation, taken from (1) EN 1194 [24], (2) Bodig and Jayne [36] and (3) friction tests

Elastic moduli		Shear Modulus	Poisson's	Coefficient of
(1)		(1)	ratio (2)	friction (3)
N/mm ²	N/mm ²	N/mm ²		
12600	420	780	0.422	0.176

gave a mean kinetic friction coefficient of 0.168 for the six tests, with a coefficient of variation of 0.15, and a mean static friction coefficient of 0.184 with a coefficient of variation of 0.11. It was considered that both the static and kinetic friction cases would be relevant during the tests, since some parts of the interface between dowel and timber would be moving relative to one another, and some would not. The mean of the two values was therefore used in the model. The influence of the friction coefficient on the predicted stiffness was found to be small in this range: the stiffness predicted using the static friction coefficient was, as a maximum for the grain and load orientations, 0.5% higher than that using the kinetic coefficient. The assumption of a single friction coefficient, taken as the mean of the two values, was therefore considered appropriate.

Table 4 shows the predicted stiffness of the embedment and single-dowel connection specimens compared with the measured stiffness in the tests with $R=1.2$. The results show that the measured stiffness under cyclic load is lower than the elastic stiffness in most of the tests, with the exception of the perpendicular-to-grain single-dowel tests.

The reason that the elastic model generally over-predicts the stiffness

Table 4: Comparison of predicted elastic stiffness with the secant stiffness measured in cyclic load tests with $R=1.2$

Grain orientation	Load direction	Predicted	Measured stiffness	
		elastic	Mean	Standard deviation
		kN/mm	kN/mm	kN/mm
Parallel to grain	Compression	41.9	39.7	5.0
Perpendicular to grain	Compression	14.5	16.7	3.7
Parallel to grain	Tension	39.7	34.5	2.9
Perpendicular to grain	Tension	13.4	13.8	3.0

435 is considered to be that it does not account for the effect of the imperfect
 436 contact surface between dowel and timber. The model assumes that the load
 437 is transferred between dowel and timber through a perfectly rigid contact.
 438 In the experiments, the surface of the timber in contact with the dowel is
 439 uneven, as a result of the drilling process, and this unevenness reduces the
 440 stiffness of the connection as a whole. The effect is most pronounced at low
 441 loads, so the $R=10$ cyclic tests, in which the load reduces to almost zero in
 442 each cycle, have a greater reduction in stiffness than the $R=1.2$ tests. The
 443 model is therefore only compared with the results of the $R=1.2$ tests.

444 The underprediction in the perpendicular-to-grain single-dowel connec-
 445 tion tests is thought to be due to the fact that the Winkler foundation in
 446 the beam-on-elastic-foundation model does not allow for distribution of load
 447 by shear in the foundation, which may be especially prevalent perpendicular
 448 to grain, since the ratio of the shear modulus to the foundation stiffness is

449 higher than in the parallel-to-grain tests.

450 The fact that the measured density of the glulam was 12% higher than the
451 standard density for GL28h according to EN1194 [24] means that the stiffness
452 of the material might be expected to be slightly higher than modelled. This
453 would have the effect of reducing, or perhaps eliminating, the underestimate
454 in the perpendicular-to-grain tests, and increasing the overestimate parallel
455 to grain.

456 6. Conclusion

457 It has been shown through experimental work that the stiffness exhibited
458 by a dowel-type connection under cyclic load depends on the nature of the
459 loads applied to it. The cyclic loads applied in this study were representative
460 of in-service vibration of a structure, in that their peak value was well below
461 the ultimate strength of the connection.

462 It was seen that the secant stiffness of the connection was highest under
463 one-sided oscillating load in which the mean load was large compared with
464 the cyclic component. In these conditions, the specimen stiffness was close
465 to that predicted by an elastic analysis consisting of a stress function for em-
466 bedment and a beam-on-elastic-foundation model for dowel bending. As the
467 amplitude of the cyclic component was increased in comparison to the mean,
468 the secant stiffness reduced, and the energy dissipation increased. Under re-
469 versed cyclic load, the oversize of the hole in the steel loading plate and gap
470 formation in the timber led to further reduction in the secant stiffness. These
471 trends were evident in both parallel- and perpendicular-to-grain specimens,
472 though a greater scatter in stiffness was observed in the perpendicular-to-

473 grain specimens.

474 In its current form, the model could be applied to estimate connection
475 stiffness for prediction of behaviour under small-amplitude one-sided dynamic
476 loads similar to those applied in the $R=1.2$ tests. An example would be
477 footfall-induced vibration of a footbridge, in which the dynamic force is small
478 in comparison with the self-weight. Further work could extend the model to
479 account for the reduction in stiffness resulting from nonlinear behaviour at
480 low load, which would enable it to be applied to a wider range of dynamic
481 in-service loads.

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